

## How can we test seesaw experimentally?

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The seesaw mechanism for the small neutrino mass has been a popular paradigm, yet it has been believed that there is no way to test it experimentally. We present a conceivable outcome from future experiments that would convince us of the seesaw mechanism. It would involve a variety of data from LHC, ILC, cosmology, underground, and low-energy flavor violation experiments to establish the case.

Recent years have seen revolutionary progress in neutrino physics [1]. What used to be invisible particles Pauli regretted proposing turned out to be a big excitement. This is thanks to the discovery of their quantum mechanical oscillation over macroscopic distances, which implies they have tiny but finite masses against the prediction of the Standard Model (SM) of particle physics. Moreover, neutrinos have relevance to many fields other than particle physics, *e.g.* nuclear physics, astrophysics, and cosmology. They may help explain why we exist at all (cosmic baryon asymmetry) [2], or why the universe is so big (inflation) if combined with supersymmetry [3].

A possible finite neutrino mass has been of great interest to physicists as a potential probe of physics at extremely high energies. To parameterize physics at a high energy  $\Lambda$ , we can systematically expand the Lagrangian in its inverse powers,

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \cdots \quad (1)$$

Here,  $\mathcal{L}_{SM}$  is the Lagrangian of the SM which is renormalizable and hence contains only operators of mass dimension four or less. Terms suppressed by inverse powers of  $\Lambda$  are non-renormalizable and represent the impact of physics at high energies as suppressed effects at low energies that we may probe in experiments. Possible operators that may be present at each order in  $1/\Lambda$  can be enumerated with the particle content of the SM. Even though there are a large number of possible operators in  $\mathcal{L}_6$  and beyond, there is only one operator one can write down in  $\mathcal{L}_5$ ,

$$\mathcal{L}_5 = \frac{1}{2} (LH)(LH). \quad (2)$$

By substituting the vacuum expectation value for the Higgs field  $v = \langle H \rangle = 174$  GeV, this is nothing but the Majorana mass of neutrinos,

$$\frac{1}{\Lambda} \mathcal{L}_5 = \frac{1}{2} \frac{v^2}{\Lambda} \nu\nu = \frac{1}{2} m_\nu \nu\nu. \quad (3)$$

Therefore, neutrino mass can be viewed as the leading order effect of physics at high energies, and hence is very important.

The most striking aspect of the discovered neutrino masses is their tininess. Compared to masses of other elementary particles, neutrino masses are seven or more orders of magnitude smaller. Following the above operator analysis, the smallness of neutrino mass  $\sim 0.1$  eV translates to extremely high energy

scales  $\Lambda \sim 10^{14}$  GeV. This is an energy scale we cannot hope to reach directly with particle accelerators.

In fact, it is incredibly fortunate that we could probe such tiny neutrino masses at all. Any kinematic effect of neutrino mass for a typical accelerator or cosmogenic neutrino are suppressed by  $(m_\nu/E_\nu)^2 \sim (0.1 \text{ eV}/1 \text{ GeV})^2 = 10^{-20}$ . Even though such tiny effects appear hopelessly small for experimental detection, interferometry may help enhance their effects to observable size. Interferometry requires three ingredients: a coherent source, the presence of interfering waves, and long baselines. Nature kindly provided us all of these for neutrinos. There are numerous coherent sources of neutrinos, including the Sun, cosmic ray interactions in the atmosphere, nuclear reactors and particle accelerators. There are interfering waves because of large mixing angles. Lastly, there are macroscopically long baselines available, such as the sizes of the Earth or the Sun. An effect as small as  $10^{-20}$  is observable thanks to such fortuitous circumstances.

Having observed tiny neutrino masses, which could well be the impact of physics at extremely high energies, we are posed with an obvious challenge. What is really going on at such high scales? The standard seesaw mechanism [4] introduces gauge-singlet right-handed neutrinos to generate the operator Eq. (3), but how will we know if this is the case? Without particle accelerators that reach such high energies, it appears that our interpretation will remain forever ambiguous. One can write many theories that would give rise to the observed tiny neutrino masses and mixings without any apparent contradiction with all available data at energy scales we can directly probe. Is there a way to overcome this deadlock? The conventional answer is no; yet the opportunity to probe physics at such high energies motivates us to seek for one.

In this Letter, we present a hypothetical yet conceivable outcome of future experiments that would convince us of the physics responsible for the tiny neutrino masses. It would require the collection of many different experimental approaches, including the Large Hadron Collider (LHC), International Linear Collider (ILC), cosmology, underground, and low-energy flavor violation experiments.

We assume three important outcomes from the future experiments. First, underground experiments establish the existence of neutrinoless double beta decay of nuclei. Second is the discovery of supersymmetry at the LHC, followed up by the ILC verifying that it is indeed supersymmetry [5] and

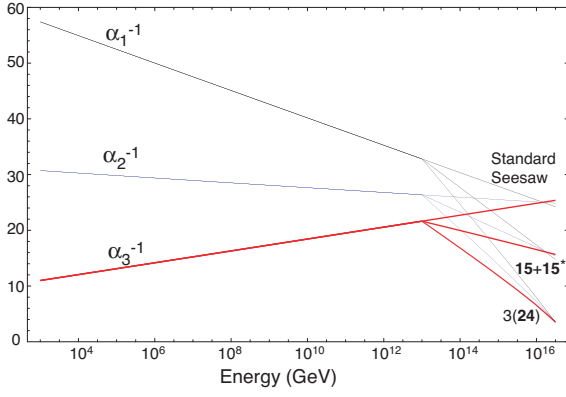


FIG. 1: The apparent unification of gauge coupling constants with the two-loop renormalization group equation (RGE) with  $m_{SUSY} \simeq 1$  TeV. Uncertainty in coupling constants from [7]. Labels indicate particle content in addition to the MSSM at  $M = 10^{13}$  GeV, listed as representations of SU(5), and “Standard Seesaw” refers to gauge-singlet right-handed neutrinos.

measuring the masses of superparticle masses precisely [6]. Third, we assume the measured masses, when extrapolated to high energies, show unification at  $M_{GUT} \sim 2 \times 10^{16}$  GeV, as already hinted by the precise measurements of gauge coupling constants. Combined, such data would go a long way towards establishing the seesaw mechanism. Gaps in such a claim can be filled in by other data such as the cosmic microwave background, large-scale structure of the universe, and searches for low-energy lepton flavor violation.

The unification of superparticle masses at  $M_{GUT}$  is the crucial aspect of the discussion. Assuming the minimal supersymmetric extension of the SM (MSSM), the gauge coupling constants apparently unify at  $M_{GUT}$ , as shown in the “Standard Seesaw” bands in Fig. 1. However, this observation may be dismissed as a pure coincidence. Two lines are bound to meet at some energy scale, while the third line meeting at the same point might happen accidentally.

However, the measurement of superparticle masses will examine whether the apparent unification is purely coincidental. First, the masses of the three gauginos, superpartners of SM gauge bosons, should unify at the same energy scale  $M_{GUT}$  if unification is true [21]. Unification of two masses would present a non-trivial test, while the unification of the third constitutes another. Such an observation would therefore add two more non-trivial coincidences. It has been shown by simulations that the combination of LHC and ILC data can provide sufficiently precise gaugino masses and hence non-trivial tests of gaugino mass unification (Fig. 2) [6, 8].

In addition, the masses of matter superpartners (sfermions) can also be measured precisely. If they exhibit the unification at  $M_{GUT}$ , then grand unification would be very difficult to dismiss. The left-handed quarks  $Q$ , right-handed up-quarks  $U$  and right-handed charged leptons  $E$  of a given generation would belong to the same multiplet, and their superpartner masses unify at  $M_{GUT}$ . If this happens for all three genera-

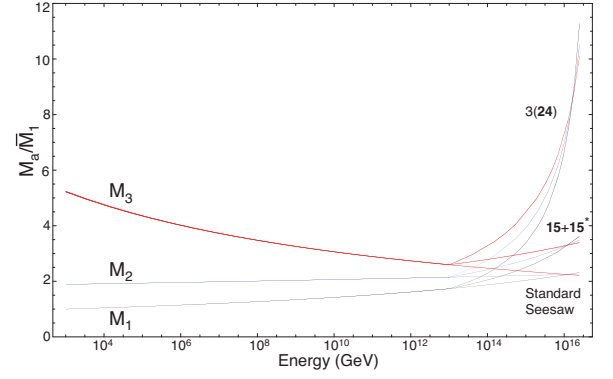


FIG. 2: The unification of gaugino masses which data from LHC and ILC may demonstrate. One-loop RGE are used with  $m_{SUSY} \simeq 1$  TeV and  $M = 10^{13}$  GeV. They are normalized by  $\bar{M}_1 \equiv M_1(1 \text{ TeV})$ . The projected accuracy of measurements is from [8]. As in Fig. 1, labels indicate particle content in addition to MSSM.

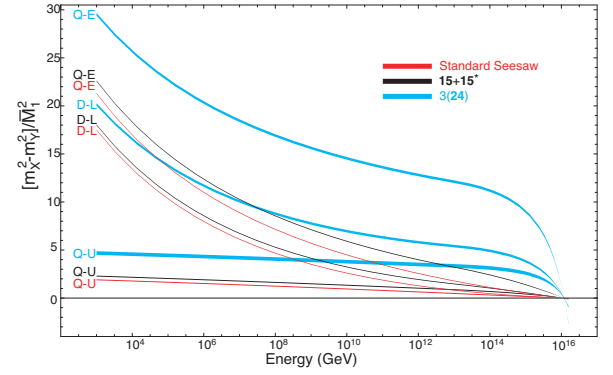


FIG. 3: Prediction on sfermion masses assuming their unification at the same  $M_{GUT}$  suggested by the gauge couplings and gaugino masses for three different particle contents at  $M = 10^{13}$  GeV.  $\bar{M}_1 \equiv M_1(1 \text{ TeV})$ , and  $m_X^2 - m_Y^2$  refer to mass squared differences between scalar  $Q$  and  $U$ ,  $Q$  and  $E$ , or  $D$  and  $L$ .

tions, it would present six more coincidences. Unification of the right-handed down quarks  $D$  and left-handed leptons  $L$  would provide three more coincidences.

The main point is that the combination of gaugino mass and sfermion mass unification provides important information about the particle content between TeV and  $M_{GUT}$  [9]. For instance, gaugino mass unification holds even if there are multiple stages of symmetry breaking as long as they are eventually unified in a single group. In addition, we see an apparent gaugino mass unification in models of gauge mediation with messengers that happen to fall into complete SU(5) multiplets [10] even if there is no true unification. On the other hand, these different possibilities give different patterns of sfermion masses and can be discriminated against. If the simple picture of unification as in the “Standard Seesaw” of Fig. 3 holds, we know it is not gauge mediation, and there is no additional stage of symmetry breaking. To the extent that we do not dismiss so many non-trivial consistency checks of unification as mere coincidences, the particle content between TeV and

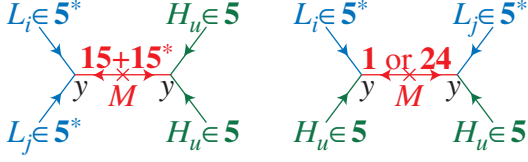


FIG. 4: Possible supergraphs which generate neutrino mass consistent with gauge coupling and gaugino mass unification.

$M_{GUT}$  would be subject to stringent constraints; namely that there cannot be any new particles with non-trivial quantum numbers under the SM gauge groups.

Such an observation would strongly favor the possibility that the neutrino masses originate from gauge-singlet particles, that is, the standard seesaw mechanism. Note that we already know the energy scale responsible for neutrino masses is substantially lower than  $M_{GUT}$ . The largest neutrino mass cannot be smaller than  $(\Delta m_{23}^2)^{1/2} \simeq 0.05$  eV, which implies  $\Lambda \lesssim 6 \times 10^{14}$  GeV  $\ll M_{GUT}$ . Additional particles needed at or below  $\Lambda$  cannot have non-trivial SM charges. We will discuss this constraint more quantitatively below.

First, we need to know that the neutrino mass is given by the operator Eq. (3). This is where underground experiments searching for neutrinoless double beta decay ( $0\nu\beta\beta$ ) of nuclei come in. Once a positive signal is established, we would conclude that neutrinos are Majorana particles and hence the operator Eq. (3) exists. In addition, the rate would also determine the energy scale  $\Lambda$ . The rate of  $0\nu\beta\beta$  determines the effective electron neutrino mass (up to uncertainties in nuclear matrix elements)  $\langle m_\nu \rangle_{ee} \equiv |\sum_i m_{\nu_i} U_{ei}^2|$ . For example  $\langle m_\nu \rangle_{ee} \simeq 0.1$  eV would translate to  $\Lambda \simeq 3 \times 10^{14}$  GeV, substantially lower than  $M_{GUT}$ . Then the question is what set of particles would produce the operator Eq. (3) with this value of  $\Lambda$ .

Second, the constraint from the gauge coupling and gaugino mass unification is that any additional particles below  $M_{GUT}$  must appear in complete SU(5) multiplets. Therefore there are only a finite number of possibilities to generate the operator Eq. (3). Because of supersymmetry, the operator needs to be in a superpotential and, due to the non-renormalization theorem of the superpotential, can only be generated by a tree-level exchange of new particles. These can be either in the  $LL$  to  $HH$  channel, or in the  $LH$  to  $LH$  channel (Fig. 4). Because we know already that at least two of the neutrinos have finite yet different masses, the  $LL$  channel must be in the symmetric combination of flavors. Since  $L$  belongs to  $5^*$  multiplet in SU(5), the symmetric combination of two  $5^*$  can only be  $15^*$ . We also need a  $15$  multiplet to avoid anomalies and allow for its mass. For the  $LH$  to  $LH$  channel, where  $H$  belongs to the  $5$ , the exchanged particle can be either in  $24$  or  $1$ . In order to generate a neutrino mass matrix of rank  $\geq 2$ , we need at least two copies of  $24$  or  $1$ . For quantitative analysis, we assume all three neutrinos have mass and hence three copies of  $24$  or  $1$ . Therefore, there are three

logical possibilities to be studied: the standard seesaw with three  $1$ , the modified seesaw with three  $24$ , and the so-called Type-II seesaw with  $15 + 15^*$ .

The effects of these extra multiplets on the running of coupling constants and gaugino masses are demonstrated in Figs. 1 and 2 for the particular choice  $M = 10^{13}$  GeV (see e.g. [11] for RGEs). As previously noted, unification at  $M_{GUT} \sim 2 \times 10^{16}$  GeV remains unchanged. Note that the scale  $\Lambda$  is not the same as the mass of these additional multiplets  $M$  because their relationship depends on the size of the Yukawa couplings  $y$  as  $\Lambda = M/y^2$ . Imposing the perturbativity of the Yukawa couplings to be consistent with perturbative unification,  $y \lesssim O(1)$  and hence  $M \lesssim \Lambda \ll M_{GUT}$ .

Third, these additional particles below  $M_{GUT}$  would affect the evolution of sfermion masses. The presence of additional particles cause larger gaugino masses above the scale  $M$  (as in Fig. 2), and hence larger RGE effects in sfermion masses-squared which are proportional to gaugino masses-squared. One can then discuss the mass-squared differences of matter superpartners in the same SU(5) multiplets in the unit of gaugino masses. We use the ratios  $(m_Q^2 - m_U^2)/\bar{M}_1^2$ ,  $(m_Q^2 - m_E^2)/\bar{M}_1^2$ , and  $(m_D^2 - m_L^2)/\bar{M}_1^2$  with  $\bar{M}_1 = M_1$  (TeV) for this purpose. At the leading order in RGE with negligible Yukawa couplings, these quantities are independent of the boundary conditions and hence allow for definite predictions. Therefore, we restrict our quantitative analysis to the leading order (i.e. one-loop), yet we stick to two-loop RGE for gauge coupling constants to be consistent with  $M_{GUT} = 2 \times 10^{16}$  GeV. Higher order RGE for sfermion masses will not change the results qualitatively [12]. For the three logical possibilities consistent with gauge coupling and gaugino mass unification, we find different values for these ratios as seen in Fig. 3 and Table I. The quantitative result obviously depends on  $M$ . The main conclusion is that the three different models can be distinguished from each other if percent level measurements on these mass ratios can be performed at the LHC and ILC and if  $M \lesssim 10^{14}$  GeV.

Can such precise measurements be done? According to the studies, the slepton and gaugino masses can be measured at permille levels at the ILC, negligible errors for our purpose. The question is the measurement of squark masses. The LHC can achieve statistical accuracy of 0.2% on measurements of squark mass, yet is limited by the systematic uncertainty in the jet energy scale expected at the 1% level [13]. At the ILC, kinematic distribution in the squark decay product would give better than 1% measurement if enough luminosity is obtained and jet energy calibrated by  $Z$  mass [14]. In addition, a threshold scan would possibly lead to a  $\sim 0.5\%$  level measurement [15]. ILC is crucial in this program because we have to differentiate different types of squarks. The required precision is challenge even for the ILC, yet it is encouraging that the measurement strategies have not yet been fully optimized.

Therefore, it is quite conceivable that LHC and ILC measurements of superparticle masses would pick one out of three possibilities for additional particle content. In particular, observation of sfermion mass unification with the MSSM parti-

$M$		$10^{15}$ GeV		$10^{14}$ GeV		$10^{13}$ GeV	
model	MSSM	$3 \times 24$	$15 + 15^*$	$3 \times 24$	$15 + 15^*$	$3 \times 24$	$15 + 15^*$
$(m_Q^2 - m_U^2)/M_1^2$	$1.90^{+0.05}_{-0.05}$	$1.98^{+0.05}_{-0.05}$	$1.93^{+0.05}_{-0.05}$	$2.41^{+0.05}_{-0.06}$	$2.04^{+0.05}_{-0.05}$	$4.68^{+0.19}_{-0.19}$	$2.29^{+0.05}_{-0.05}$
$(m_Q^2 - m_E^2)/M_1^2$	$21.30^{+0.03}_{-0.04}$	$21.41^{+0.03}_{-0.04}$	$21.35^{+0.03}_{-0.04}$	$22.58^{+0.04}_{-0.04}$	$21.70^{+0.04}_{-0.04}$	$29.52^{+0.14}_{-0.13}$	$22.60^{+0.04}_{-0.04}$
$(m_D^2 - m_L^2)/M_1^2$	$17.48^{+0.05}_{-0.03}$	$17.50^{+0.03}_{-0.04}$	$17.49^{+0.03}_{-0.03}$	$17.77^{+0.04}_{-0.04}$	$17.62^{+0.04}_{-0.04}$	$20.15^{+0.13}_{-0.13}$	$18.02^{+0.04}_{-0.04}$

TABLE I: The predicted mass ratios at 1 TeV for three different possible origins of neutrino mass consistent with gauge coupling and gaugino mass unification, for three values of heavy particle mass  $M$ . The errors are due to uncertainties in the observed gauge coupling constants and expected experimental uncertainties in the gaugino mass.

cle content would mostly likely convince us that unification is real, and hence exclude the additional gauge non-singlet particles below  $M_{GUT}$  as in the modified Type-I or Type-II models. By process of elimination, it would establish the SM singlets as the origin of neutrino masses, and hence the standard seesaw mechanism.

This result would also tell us something about the origin of baryon asymmetry. Note that the tremendous success of the inflationary paradigm suggests the baryon asymmetry must be generated by physics at or below the inflationary scale  $H_{inf}$ . The current cosmological data provide an upper limit  $H_{inf} \leq 1.5 \times 10^{14}$  GeV [16]. Therefore, in generic inflationary models [22], baryogenesis would require particles  $\lesssim 10^{14}$  GeV, and hence they would affect the scalar mass unification if not gauge singlets. Once scalar mass unification is confirmed, baryogenesis must be either due to particles in the MSSM, namely electroweak baryogenesis, or due to gauge-singlets beyond the MSSM. The former can in principle be excluded experimentally (*e.g.*, searches for light  $\tilde{t}$  and  $\chi^\pm$  and electric dipole moments [17] and  $B$  physics [18]). This would then require baryogenesis by gauge-singlets, hinting very strongly at leptogenesis [2]. In a similar fashion, we could obtain interesting restrictions on various axion models which also require additional gauge non-singlet particles  $\lesssim 10^{12}$  GeV.

We have to mention potential loopholes with the whole argument. First, the observation of  $0\nu\beta\beta$  would not necessarily establish the Majorana neutrino mass as the dominant contribution. It could be, for example, due to  $R$ -parity violating supersymmetry or extended gauge sector.  $R$ -parity violation can be excluded if the collider measurements of superparticle spectrum and couplings gives the cosmic abundance of the lightest supersymmetric particle consistent with the cosmological data (see, *e.g.*, [19]). Extended gauge sectors necessarily require additional particles below  $M_{GUT}$  which are also excluded by sfermion mass unification. Second, running of sfermion masses may also be affected by the neutrino Yukawa couplings  $y$  if they are close to  $O(1)$ . However, such large  $y$  tend to lead to sizable lepton-flavor violation. In fact, the present upper limit on  $\mu \rightarrow e\gamma$  combined with the now-established large mixing angle solution to the solar neutrino problem already requires small  $y$ , and hence favors  $M \lesssim 10^{13}$  GeV for moderate values of supersymmetric parameters [20]. Future improvements on upper limits on such processes combined with supersymmetric parameters

from colliders would yield stronger upper limit on the mass  $M$  which can only strengthens the result.

We have presented a hypothetical yet conceivable outcome from future experiments that would establish the standard seesaw mechanism. It is surprising that collider measurements of superparticle masses would be the crucial information, while additional information from  $0\nu\beta\beta$ , cosmological abundance of dark matter, and low-energy lepton flavor violation would fill in the gaps. This way, we may use the neutrino masses as real probe to physics at extremely high energy scales.

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